Adaptive Distance Protection for Transmission Lines Incorporating SSSC With Energy Storage Device

H. V. GURURAJA RAO[ID1], NAGESH PRABHU[2], (Senior Member, IEEE), AND R. C. MALA[1]
[1]Department of Electrical and Electronics Engineering, Manipal Institute of Technology (MAHE), Manipal 576104, India
[2]Department of Electrical and Electronics Engineering, N.M.A.M. Institute of Technology (Nitte), Karkala 574110, India

Corresponding author: H. V. Gururaja Rao (gururaj.rao@manipal.edu)

ABSTRACT A Static Synchronous Series Compensator incorporating energy storage device (SSSC-ES) at the DC bus enables the exchange of true power with the system in addition to line reactance compensation. This facilitates improved control of real and reactive power in a transmission system. However, the four-quadrant operation of SSSC presents additional problems for the accurate operation of conventional transmission line protection. In this paper, an in-depth analysis of the effect of emulated reactance and resistance by SSSC-ES installed at the center of a hybrid series compensated line on the performance of distance relay is carried out. An investigation is performed with all possible operating modes and control strategies of SSSC-ES, and the possibility of mal-operation of distance protection are explored. A novel adaptive setting based on constant reactance and constant resistance emulation control strategy of SSSC is proposed for quadrilateral distance relay to prevent the mal-operation. MATLAB / SIMULINK is used for the simulation study.

INDEX TERMS Emulated reactance and resistance, SSSC with energy storage, quadrilateral distance relay, under reach and over reach, adaptive relay setting.

I. INTRODUCTION

FACTS controllers make the AC transmission system flexible by enhancing system controllability and power transfer capability [1]–[3]. Series FACTS controllers are mainly used to compensate for the line reactance and hence to control power transfer in long transmission lines. Series FACTS controllers also enhance the transient stability of a mixed AC/DC system [4]. For economic reasons, it is preferable to use a combination of a fixed series capacitor, and a voltage source controller (VSC) based SSSC [5]. An added advantage of SSSC is the provision for integrating an energy storage device (battery, fuel cell, or Super Conducting Magnetic Energy Storage) for real power supply/absorption. It results in ''enhancement of power transfer control, transient stability improvement, and power oscillation damping'' [6].

Non-availability of the main transmission line will result in loss of power to a large section of the system and economic loss to both the supplier and the customer. Therefore, protection scheme for lines should ensure reliable and fast operation to localize the damage and maintain transient stability.

The associate editor coordinating the review of this manuscript and approving it for publication was Dongbo Zhao.

Distance protection is the most favored scheme for primary transmission lines, and the current practice is to adopt digital protection techniques [7], [8]. During system disturbance, compensation of transmission lines by series or shunt connected FACTS controllers results in modification of primary power system parameters due to control actions. Conventional distance relay performance is expected to be impacted by the operation and control of FACTS controllers. Few researchers have investigated the impact of FACTS controllers on the accuracy of distance relay operation. Efficacy of digital distance relay due to the operation of series FACTS controllers is studied in [9]–[11]. References [12]–[14] discusses the impact of shunt connected FACTS controllers and factors affecting distance protection of UPFC compensated lines is investigated in [15]. Adaptive distance protection for lines integrating FACTS controllers is described in [16]–[19]. Work reported considers a limited range two-quadrant operation of SSSC and STATCOM without energy storage device.

SSSC without an energy storage device can operate only in a limited reactance compensation range. It injects a reactive voltage and negligibly small real voltage to meet the converter and capacitor losses. The angle of injected voltage
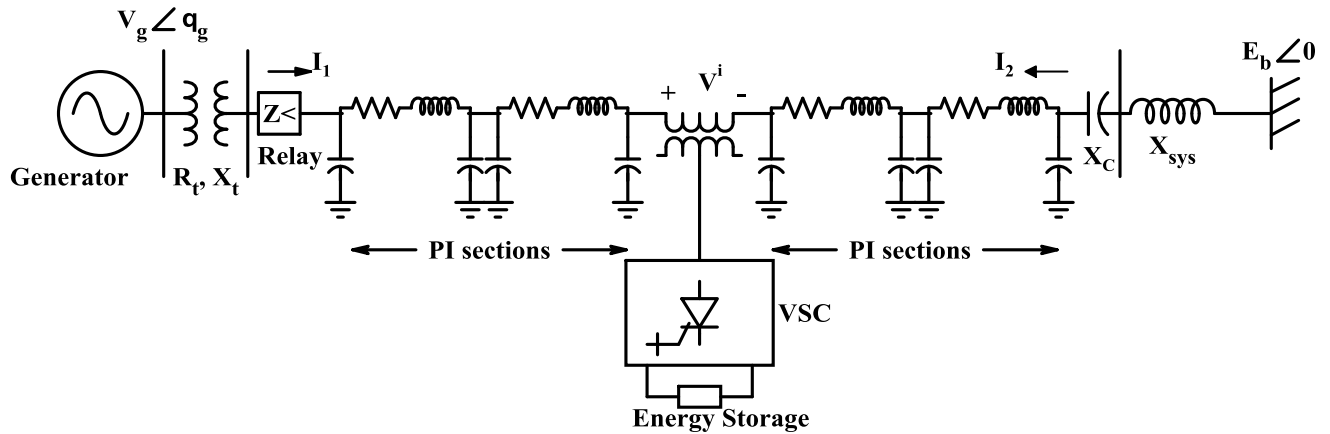
with the line current is close to $\pm 90°$. With an energy storage device, real voltage injected by SSSC can be zero, large positive or large negative, and the operating region is much broader, encompasses all the four quadrants. The angle of the injected voltage can be between 0° and 360°.

Limited work is reported on the analysis of the impact of FACTS controllers incorporating energy storage devices on power system operation and control. In [20], change in "steady-state characteristics of SSSC equipped with energy storage" is highlighted. Transient stability enhancement with a unified STATCOM–fuel cell is discussed in [21]. However, the effect of an energy storage device connected at the DC bus of FACTS controllers on distance relay operation is not investigated. Initial attempts have thrown some light on the effect of integrating energy storage device (SMES) with SSSC and UPFC on the performance of transmission line protection [22], [23]. However, the effect of emulated reactance and resistance by SSSC and control strategy for SSSC on distance relay performance is not analyzed thoroughly. Emulated reactance and resistance by SSSC with an energy storage device is presented in [24]. However, the impact on distance relay performance during fault is not investigated. SSSC without energy storage emulates positive or negative reactance and negligible positive resistance to meet the losses of SSSC. Hence only reactance seen by distance relay is expected to get modified. However, SSSC with energy storage emulates large positive or negative resistance. Thus both the reactance and resistance seen by distance relay get modified substantially. The impact of control strategy adapted for SSSC-ES on the impedance measured by distance relay, during fault is not thoroughly investigated. There is no reported work on adaptive distance relay setting for lines compensated with SSSC–ES based on emulated reactance and resistance. The foremost aim of this work is to thoroughly study and analyze the impact of emulated reactance and resistance by four-quadrant operation of SSSC and various control strategies for SSSC on the performance of conventional distance relay. A new methodology for adaptive relay setting based on the

computation of emulated resistance and reactance of SSSC to prevent the relay mal-operation is presented.

II. SYSTEM MODEL

FIGURE 1 shows the test system adapted from IEEE first benchmark model [25].

Here 'R_t' and 'X_t' are the resistance and reactance of transformer, 'X_C' is the capacitive reactance of passive series capacitor, and 'X_{sys}' is the system reactance on the infinite bus side. 'E_b' is the infinite bus voltage. The relay shown in FIGURE 1 ($Z <$) is a distance relay at the generator end of the line, which operates when the measured impedance is less than the set impedance. SSSC-ES is installed at the midpoint of the 200Km line. The transmission line is divided into four PI sections to simulate fault at any desired line length, before or after the location of SSSC.

A. SYSTEM EQUATIONS
A 3-level, 12-pulse SSSC is used to reduce harmonics [5]. A DQ model of the system is used for analysis.

Injected voltage by SSSC-ES,

$$V^i = \sqrt{V_Q^{i2} + V_D^{i2}} \qquad (1)$$

where, $V_D^i = K_m * V_{dc} * sin(\Phi + \gamma)$ $\qquad (2)$

$$V_Q^i = K_m * V_{dc} * cos(\Phi + \gamma) \qquad (3)$$

where $K_m = K * \rho_{se} * cos\beta$; $K = \frac{2\sqrt{6}}{\pi}$ for a 12 pulse converter, 'ρ_{se}' is the turns ratio of the transformer and

$$\Phi = \tan^{-1}\left(\frac{i_D}{i_Q}\right) \qquad (4)$$

From the control point of view, real (in-phase) and reactive (quadrature) voltages are defined for SSSC as

$$V_P = V_D^i sin\Phi + V_Q^i cos\Phi \qquad (5)$$

$$V_R = V_D^i cos\Phi - V_Q^i sin\Phi \qquad (6)$$

A positive value of V_P implies SSSC-ES absorbing real power, and negative V_P implies SSSC-ES supplying real
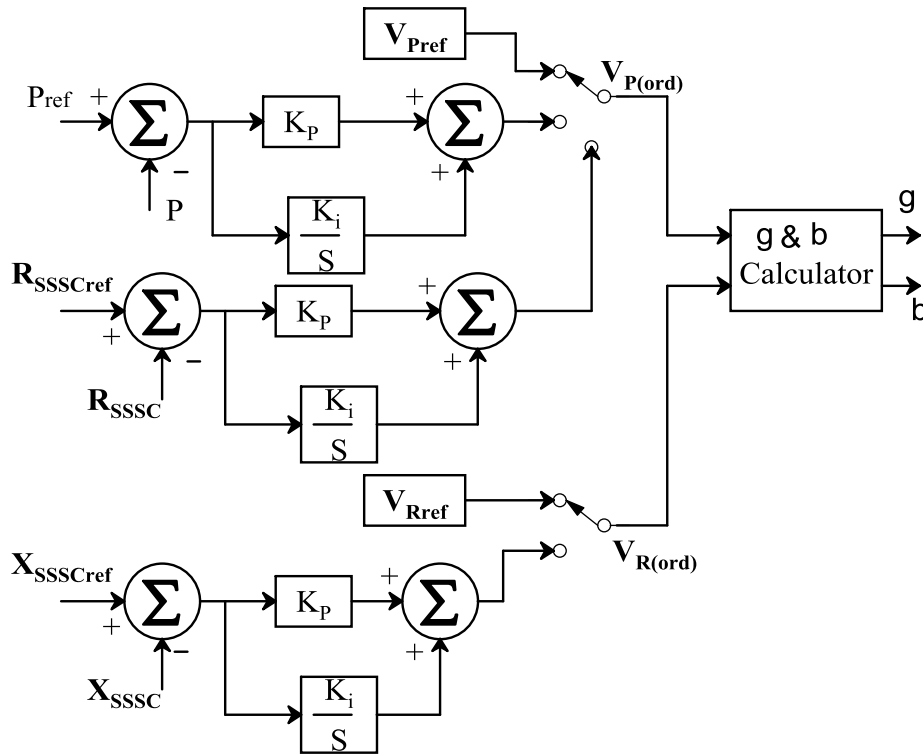
FIGURE 2. Type 1 controller for SSSC-ES.

power. In capacitive mode, V_R is negative and is positive in inductive mode.

Angle of SSSC injected voltage,

$$\gamma = \tan^{-1}\left(\frac{V_{R(ord)}}{V_{P(ord)}}\right) \quad (7)$$

Deadangle, β

$$= \text{Cos}^{-1}\left(\frac{\sqrt{V_{P(ord)}^2 + V_{R(ord)}^2}}{k * \rho_{se} * V_{dc}}\right) \quad (8)$$

Line current, I

$$= \sqrt{i_Q^2 + i_D^2} \quad (9)$$

$$\frac{di_Q}{dt} = \frac{W_b}{X_l}\left[V_{gQ} - E_{bQ} - i_Q R_l + X_l i_D - V_Q^i - V_{cQ}\right] \quad (10)$$

$$\frac{di_D}{dt} = \frac{W_b}{X_l}\left[V_{gD} - E_{bD} - i_D R_l - X_l i_Q - V_D^i - V_{cD}\right] \quad (11)$$

where, $R_l = R_t + R_{line}$ and $X_l = X_t + X_{line} + X_{sys}$

R_{line} and X_{line} are the resistance and inductive reactance of the transmission line.

Magnitude of generator voltage and the power delivered by the generator are given by

$$V_{gm} = \sqrt{V_{gQ}^2 + V_{gD}^2} \quad (12)$$

$$P_g = V_{gQ} * i_Q + V_{gD} * i_D \quad (13)$$

Reactive voltage injected by SSSC-ES,

$$V_R = (X_{SSSC} * I) = V_D^i * Cos\varphi - V_Q^i * Sin\varphi \quad (14)$$

Real power drawn by SSSC-ES,

$$P = i_D * V_D^i + i_Q * V_Q^i \quad (15)$$

B. CONTROL STRATEGIES

When SSSC is integrated with energy storage, type 1 controller is commonly employed to control both $|V^i|$ and γ. To decide real voltage injection, V_P can be held constant or constant R_{SSSC} control or constant P control can be employed. Similarly, to decide reactive voltage injection, V_R can be maintained constant or constant X_{SSSC} control can be employed, as shown in FIGURE 2. The values of K_P and K_i for all the PI controllers are obtained by root locus design and transient analysis [26].

III. METHODOLOGY

Power delivered by the generator ($P_g.$) is fixed at 0.9 pu. DC voltage of SSSC is assumed to be maintained constant at 0.7 pu by the energy source.

In the system considered for analysis, the rating of the SSSC is 150 MVA. With base MVA of 892.4 MVA and line current of 1 pu, $|V_{max}^i|$ is found to be 0.16809 pu. The system has a fixed series capacitor with a capacitive reactance of 0.45 pu. Considering a series reactance compensation range of 30% to 60%, range of X_{SSSC} is taken as from -0.15 pu (capacitive) to 0.15 pu (inductive). In order to fix the range of P_{ref}, $'V^i$ ' is determined for various operating modes, and the values obtained are tabulated in TABLE 1 (all values are in pu).

TABLE 1. SSSC parameters under steady state condition.

Operating mode	V^i	I
Xsssc = - 0.15, Pref = 0	0.1382 ∠- 90°	0.921∠ 17.15°
Xsssc = - 0.15, Pref = 0.08	0.1617 ∠-56.72°	0.9014 ∠26.72°
Xsssc = - 0.15, Pref = - 0.08	0.1669 ∠-119.8°	0.9657 ∠ 10.14°
Xsssc = 0.15, Pref = 0	0.1475 ∠90°	0.9833 ∠ 26.45°
Xsssc = 0, Pref = 0.15	0.1663 ∠0°	0.9023∠34.94°

The following equations are used to determine the impedance contribution by SSSC-ES.

$$R_{SSSC} = \frac{V_P}{|I|} \text{ and } X_{SSSC} = \frac{V_R}{|I|}$$

With reactance compensation by SSSC-ES of $\pm$ 0.15pu, the range of P_{ref} is from -0.08pu to 0.08pu. Whereas without reactance compensation by SSSC (Xsssc = 0), P_{refmax} is 0.15pu (absorbing or supplying).

A. EFFECT OF DC OFFSET ON COMPUTATION OF IMPEDANCE AND RELAY OPERATION

It is a well-known fact that a short circuit fault current contains two components, steady-state fault current (AC component) and decaying DC component. RMS value of current with DC offset will be more than the RMS value of the AC component. Hence, the distance relay may mal-operate i.e., it may over reach. Also, the presence of the DC component leads to inaccurate results from the DFT algorithm to compute the fundamental component. Thus it is necessary to get rid of the DC offset from current and voltage signals. A digital mimic impedance based filter is used to eliminate the DC offset [27]. The time constant of the digital mimic filter is selected as the time constant $\left(\frac{L}{R}\right)$ of the transmission line. After removing the DC offset component, the DFT algorithm is used to obtain the fundamental component of voltage and current. General DFT expression for the determination of mth harmonic component is given by

$$X(m) = \frac{2}{N} * \sum_{n=0}^{n=N-1} x(n) e^{-\frac{j*2\pi mn}{N}} \tag{16}$$

where m = 1 for fundamental component, 'n' is the current sample and 'N' represents the samples taken during one cycle of power frequency. Full cycle DFT algorithm is used because of its superior performance in filtering harmonics and noise. Using the above expression, the fundamental components of voltage, current are determined and Z_{relay} is computed.

IV. RESULTS AND DISCUSSION
A. STEADY STATE CONDITION

Initially, analysis is carried out without any system disturbance (No fault). Directional quadrilateral distance relay having $-15°$ directional angle setting and 115° negative restrain angle setting [28] is considered. Impedance of the line is

$Z = (0.04 + j1)$ pu. Zone 1 reach of the distance relay is assumed to be 80% of the protected line. Hence reactance setting for the distance relay is, Xset = 0.8 pu. A fault resistance of 15Ω (0.0455 pu) is considered to select a resistance setting for the relay. Hence resistance setting for the relay is Rset = 0.032+0.045 = 0.077 pu. These values are used as the zone 1 relay settings for the relay at the generator end in the various case studies considered for the analysis.

Analytically impedance values can be obtained using the following equations.

Impedance offered by SSSC,

$$Z_{SSSC} = \frac{V^i}{I} \tag{17}$$

Apparent impedance seen by relay,

$$Z_{relay} = Z_{line} + Z_{SSSC} - jX_C + jX_{Sys} + \frac{E_b}{I} \tag{18}$$

1) REACTANCE COMPENSATION

As discussed in section III, keeping the reactance compensation by series capacitor fixed at 45%, net reactance compensation can be varied from 30% to 60%. Impedance values obtained for 60% and 30% net compensation levels are presented in TABLE 2 and the plot of Z_{relay} on R − X plane is shown in FIGURE 3.

TABLE 2. Normal condition; reactance emulation.

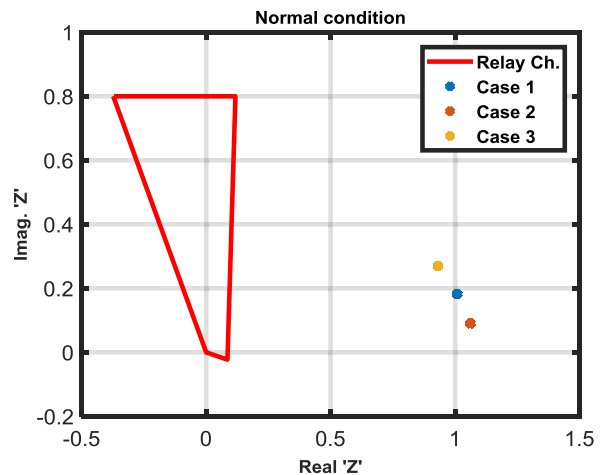| Operating mode		Z_{SSSC}	Z_{relay}
Case 1	No SSSC	0 + j 0	1.008 + j0.18226
Case 2	Xsssc = - 0.15, P_{ref} = 0	0-j0.1499	1.0609+ j0.090585
Case 3	Xsssc = 0.15, P_{ref} = 0	0+j0.1499	0.93093+ j0.26948

FIGURE 3. Zrelay, Reactance emulation by SSSC–ES.

Change in the operating condition of SSSC-ES will result in a change in line current as well (see TABLE 1). Hence, as per equation (18), both resistance and reactance seen by

TABLE 3. Impedance under normal condition, resistance emulation.

Operating mode		Z_{SSSC}	Z_{relay}
Case 4	Xsssc = 0, Pref = 0.08	0.095698 +j0	1.0766 + j0.05243
Case 5	Xsssc = 0, Pref = - 0.08	- 0.08106 + j 0	0.91205 + j0.28594

the relay will be different for various operating modes of SSSC-ES. However, from FIGURE 3, it is clear that the relay does not operate since Z_{relay} is outside the relay characteristics.

2) RESISTANCE COMPENSATION

While exchanging real power, SSSC-ES injects a voltage in phase or anti-phase with the line current. Hence it emulates positive resistance (absorbing real power) or negative resistance (supplying real power). TABLE 3 shows the impedance values with SSSC–ES exchanging real power alone, and FIGURE 4 shows the impedance plot.
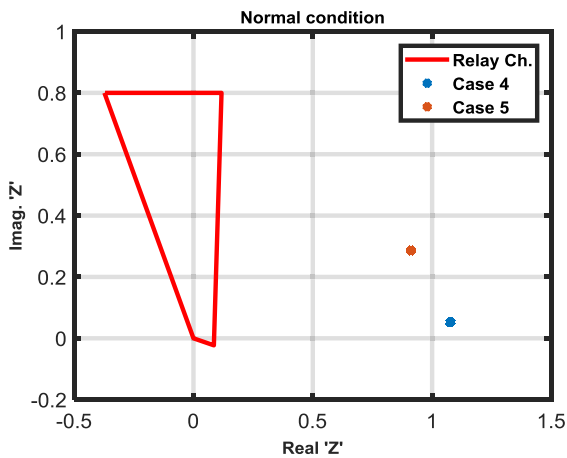

FIGURE 4. Zrelay, Resistance emulation by SSSC–ES.

Distance relay will not operate, since Z_{relay} measured is outside the set impedance.

B. THREE PHASE FAULT ON THE LINE SSSC NOT IN FAULT LOOP

The impact of operation of SSSC-ES on the relay efficacy, during fault, is studied by considering a three-phase fault on the line. Constant 'P' and constant V_R control strategy is used for SSSC in case of case studies 6 to 14. The effect of other control strategies and unsymmetrical faults is investigated in sections IV. C and D.

In case of symmetrical fault at a distance 'x' pu on the line, with zero fault impedance, following expressions are used to determine analytically the impedance measured by the relay. For faults up to 50%-line length (SSSC outside fault loop),

$$Z_{relay} = Z_{line} * x \qquad (19)$$

For faults between 50% and 100%-line length, SSSC is in the fault loop and hence,

$$Z_{relay} = Z_{line} * 0.5 + (1 - x) * Z_{line} + Z_{SSSC} \qquad (20)$$

Analytical and measured values of Z_{relay} during various operating modes of SSSC- ES for a three-phase fault at 25% is shown in TABLE 4 and it almost matches with values obtained analytically using equation (19).

TABLE 4. Fault at 25%, SSSC outside the fault loop.

Operating mode		Z_{relay}(analytical)	Z_{relay}
Case 6	No SSSC	0.01 + j0.25	0.009988 + j0.24996
Case 7	Xsssc = - 0.15, Pref = 0	0.01 + j0.25	0.009989 + j0.24997
Case 8	Xsssc = - 0.15, Pref = 0.08	0.01 + j0.25	0.009988+ j0.24996

The plot of Z_{relay} is shown in FIGURE 5. SSSC is installed at the midpoint of the line. Hence for a fault at 25% of line length, SSSC is outside the fault loop and thus Z_{relay} is not impacted by the operating mode of SSSC-ES. Hence SSSC will not affect distance relay operation for any fault on the line till 50%- line length.
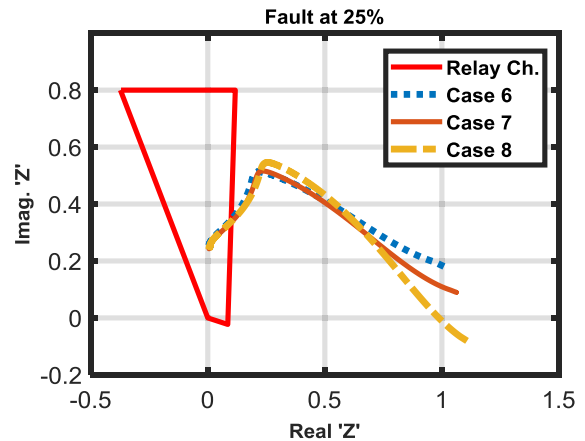

FIGURE 5. Zrelay, SSSC not in fault loop.

1) SSSC IN FAULT LOOP, REACTANCE COMPENSATION

For a three-phase fault at 75%-line length, with reactive voltage injection only (both inductive and capacitive modes of operation), obtained values of Z_{relay} is tabulated in TABLE 5. FIGURE 6 gives the obtained impedance locus.

It is evident from TABLE 5 that measured, and analytical values of Z_{relay} during fault for a given operating mode of SSSC are different since constant reactive voltage control is used for SSSC-ES. During a fault, line current increases, and hence with the injected voltage of SSSC held constant, emulated reactance by SSSC decreases. Further, it is noted from FIGURE 6 that zone 1 relay unit under reaches for a

TABLE 5. Fault at 75%, reactance emulation.

Operating mode		Z_{SSSC}	Z_{relay}(analytical)	Z_{relay}
Case 9	No SSSC	0 + j 0	0.03+ j0.75	0.03006 +j0.75
Case 10	Xsssc = - 0.15, Pref = 0	0-j0.1081	0.03 + j0.6	0.03003 +j0.64
Case 11	Xsssc = 0.15, Pref = 0	0+j0.1186	0.03 + j0.9	0.0318 +j0.871

TABLE 6. Fault at 75%, Resistance emulation.

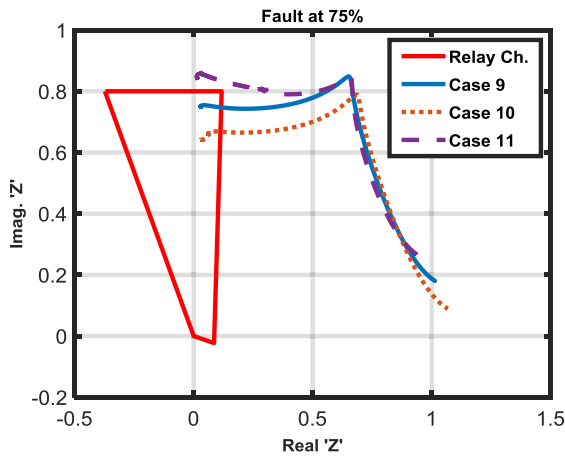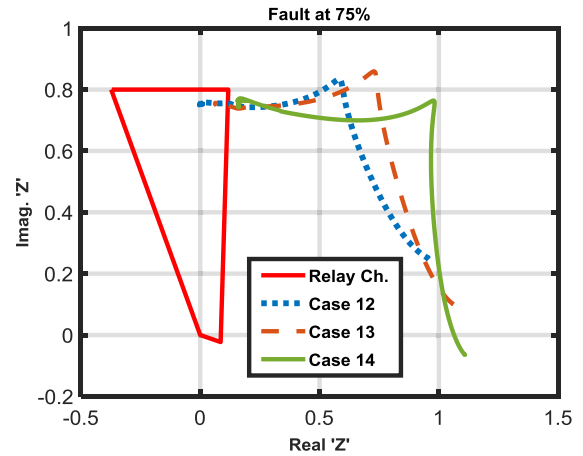| Operating mode		Z_{SSSC}	Z_{relay}
Case 12	Xsssc = 0, Pref = -0.05	-0.034222+j 0.0048993	-0.0063811 + j0.75203
Case 13	Xsssc = 0, Pref = 0.05	0.033602-j 0.0030332	0.066561 + j0.75106
Case 14	Xsssc = 0, Pref = 0.15	0.15474-j0.0013413	0.19406 + j0.75788

FIGURE 6. Zrelay, SSSC in fault loop.

FIGURE 7. Zrelay, SSSC in fault loop.

fault at 75% in case of the inductive mode of operation of SSSC-ES (case 11), because of positive reactance emulation. Similarly, in the capacitive mode of operation (case 10), Z_{relay} during fault has decreased. This is likely to make the relay over reach.

2) RESISTANCE COMPENSATION
To analyze the effect of real power exchange by SSSC-ES on the distance relay operation, the following operating modes are considered for a three-phase fault at 75%. Reactive voltage injection is zero.

Case 12: SSSC-ES supplying power (Pref = - 0.05 pu)
Case 13: SSSC-ES absorbing power (Pref = 0.05 pu)
Case 14: SSSC-ES absorbing power (Pref = 0.15 pu)

Obtained values of Z_{relay} and Z_{SSSC} are tabulated in TABLE 6, and the impedance locus is plotted in FIGURE 7. When SSSC-ES supplies power, Z_{relay} decreases due to negative resistance emulation, and when SSSC-ES draws power, apparent resistance increases due to positive resistance emulation.

It can be further observed that with increase in positive resistance emulation, measured impedance moves towards the boundary of relay characteristics. This can lead to the relay under reach, if SSSC-ES absorbs more power (emulates a higher value of positive resistance) as evident from FIGURE 7 (case 14, with Pref = 0.15)).

C. IMPACT OF CONTROL STRATEGY
Various control strategies considered for the analysis are described in section II B. During short circuit fault, the current increases. Hence, from the equation (17), it is clear that if the control strategy is to maintain SSSC injected voltage constant (constant V_P and V_R), impedance contribution by SSSC decreases. If the control strategy is to maintain emulated resistance and reactance of SSSC-ES constant (constant Rsssc and constant Xsssc control), the controller will try to maintain the impedance emulated during fault at the corresponding pre-fault value. However, this would call for an increase in SSSC injected voltage (as per equation (17)). Hence limiting the injected voltage by SSSC-ES within the rating of SSSC-ES, impedance offered by SSSC-ES during fault will be slightly different from the corresponding values during the steady-state condition, even with constant R_{SSSC} and constant X_{SSSC} control. The following case studies illustrate the impact of the control scheme for SSSC on the relay operation.

Case 15: Constant V_P, Constant V_R control (Fault at 85%-line length, $X_{SSSC} = -0.15$, Pref = 0.08).
Case 16: Constant X_{SSSC}, R_{SSSC} control (Fault at 85%-line length, $X_{SSSC} = -0.15$, Pref = 0.08).

The pre-fault emulated impedance of SSSC-ES is (0.09847-j0.15). TABLE 7 shows the measured values of Z_{SSSC} and Z_{relay} during the fault. Referring to TABLE 7, it is observed that, emulated impedance by SSSC during the fault is nearly the same as the pre-fault value, for constant resistance and constant reactance control strategy (case 16).

This is due to the fact that SSSC-ES will inject a higher voltage to maintain the emulated impedance constant during a fault condition. However, when constant V_P and constant V_R control strategy (case 15) is adapted, the emulated R_{SSSC} and X_{SSSC} during fault is substantially decreased in comparison to prefault values. This is not surprising as the SSSC injected voltage is held constant, and an increase in line current during fault leads to decreased emulated impedance. It is seen from FIGURE 8 that the distance relay over reaches and mal-operates with constant V_P, V_R control, whereas the relay does not mal-operate with constant X_{SSSC}, R_{SSSC} control. This clearly demonstrates that apparent impedance measured by the relay and hence the extent of the relay under reach or over reach depends on the control strategy of SSSC as well.

TABLE 7. Effect of control strategy on measured impedance.

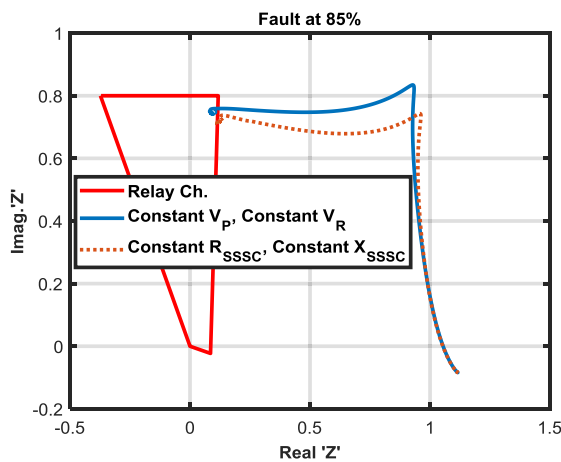| Operating mode	Z_{SSSC}	Z_{relay}
Case 15	0.071593 -j0.095955	0.10295+j0.74987
Case 16	0.09467 - j0.1395	0.13534 +j 0.72073

FIGURE 8. Zrelay, Effect of control strategy.

D. EFFECT OF UNSYMMETRICAL FAULTS

A computational algorithm for the distance relay is implemented in such a way that Z_{relay} is the positive sequence impedance up to the fault, regardless of the fault type (Symmetrical / Unsymmetrical) [29].

The following case studies illustrate the impact of SSSC on distance relay operation during unsymmetrical faults.

1) Fault at 75%; No SSSC
2) Fault at 75%, SSSC-ES operating in 4th quadrant, capacitive mode, absorbing real power (X_{sssc} = - 0.15, Pref = 0.08).

It is interesting to note from FIGURE 9 (a) and 9 (b) that for a given fault location and operating mode of SSSC-ES, the apparent impedance seen by the relay is almost independent of fault type. It is further observed from FIGURE 9 (b) that the apparent reactance is decreased due to capacitive

reactance compensation by SSSC, and apparent resistance is increased due to positive resistance emulation by SSSC. This results in under reach of distance relay for all fault types.
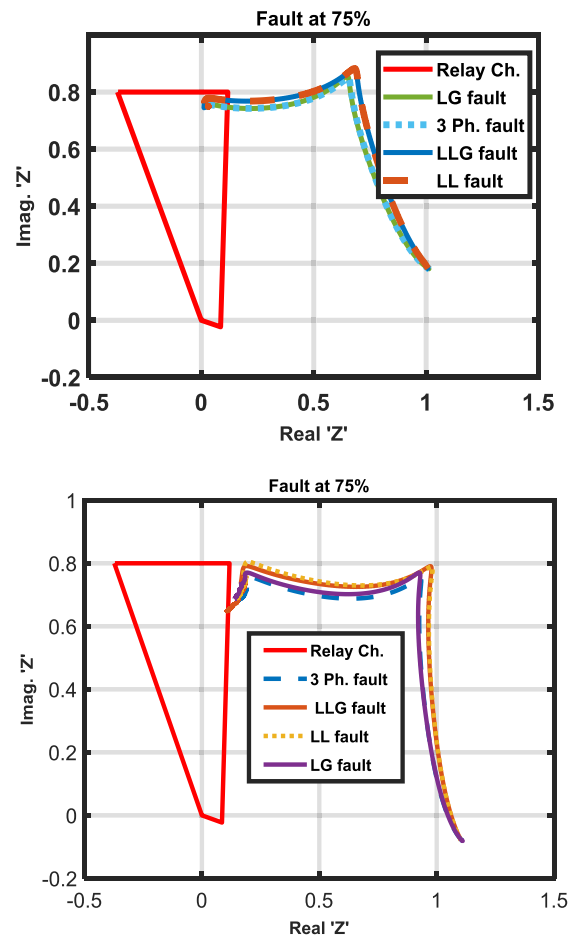

FIGURE 9. (a) Zrelay, No SSSC. (b) Zrelay, Capacitive, absorbing power.

E. ADAPTIVE RELAY SETTING TO AVOID MAL-OPERATION

The preceding sections clearly show that distance relay will mal-operate (over reach or under reach) depending on the operating mode and control strategy of SSSC-ES. With constant V_P and constant V_R control strategy, emulated impedance by SSSC-ES during fault can be estimated, and a lookup table can be prepared. This lookup table can be used to modify the relay setting in relation to change in the operating mode of SSSC. However, in constant V_P and constant V_R control strategy, emulated impedance by SSSC for a given operating mode of SSSC will also depend on the fault location. If the fault is close to SSSC location, emulated impedance by SSSC will decrease substantially due to high fault current. Hence adaptive relay setting to avoid relay mal-operation is almost impossible in constant V_R, V_P control.

In the case of constant X_{SSSC} and constant R_{SSSC} control strategy of SSSC, emulated impedance by SSSC for a given operating point, during fault will almost be the same as the prefault impedance and is independent of the fault

location. Hence constant reactance and constant resistance control strategy is best suited for adaptive relay setting in case of lines compensated with SSSC-ES. Emulated reactance and resistance values obtained for several operating modes of SSSC-ES can be utilized to dynamically modify relay settings accordingly and thus prevent the mal-operation of the distance relay. Adjustment of relay setting corresponding to change in the operating mode of SSSC-ES can be easily implemented with numerical quadrilateral distance relay with proper communication to the relaying point. The following two case studies validate this.

1) AVOIDING RELAY OVERREACH WITH ADAPTIVE RELAY SETTING

In section IV B, it is clearly shown that relay will under reach in the inductive mode of operation and the relay may over reach for the capacitive mode of operation. For capacitive mode with $X_{SSSC} = -0.15pu$, prefault emulated reactance by SSSC–ES is - j0.15 pu. Hence decreasing the set reactance (X_{set}) by 0.15pu, relay characteristics is modified, as shown in FIGURE 10. It is found that the relay over reaches and operates for a fault beyond the zone reach (fault at 85%) with standard relay characteristics. It is evident from FIGURE 10 that with modified relay characteristics, distance relay will not over reach and mal-operate.
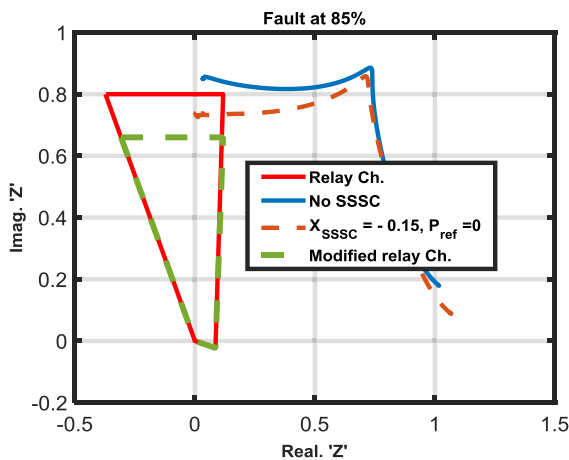
FIGURE 10. Reactance setting.

2) AVOIDING RELAY UNDER REACH WITH ADAPTIVE RELAY SETTING

From section IV B, it is very clear that the relay will under reach when SSSC-ES absorbs power due to positive resistance emulation.

With SSSC-ES absorbing power (Pref = 0.15), pre-fault emulated R_{SSSC} is 0.184pu. Hence the relay characteristics is modified by increasing the set resistance (R_{set}) by 0.184pu, as shown in FIGURE 11. The distance relay under reaches for a fault at 75%, with standard relay characteristics. It is encouraging to note that with modified relay characteristics, the distance relay will not under reach and operates correctly.
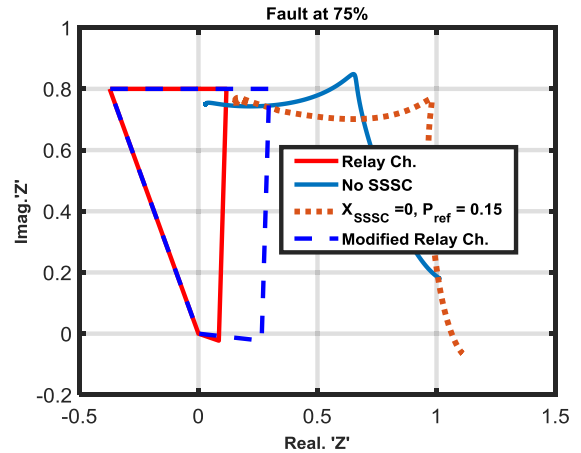
FIGURE 11. Resistance setting.

F. DISCUSSION

Based on the studies carried out, the following inferences are drawn.

- Under the steady-state condition, it is shown that distance relay operation is not affected by SSSC-ES when it is used within the rated operating range.
- When SSSC-ES is not in fault loop, distance relay operation is not affected by SSSC-ES.
- When SSSC-ES is in fault loop, Z_{relay} is dependent on operating mode and the control strategy used for SSSC-ES. Thus the operation of conventional distance relay with standard settings is not reliable.
- In the capacitive mode of operation, the distance relay will over reach due to negative reactance emulation and in inductive mode of operation, the relay will under reach due to positive reactance emulation.
- While absorbing real power, the distance relay will under reach due to positive resistance emulation, and while supplying real power, it may over reach due to negative resistance emulation.
- Extent of over reach and under reach also depends on the control strategy used for SSSC-ES.
- For a given operating mode of SSSC-ES and fault location, Z_{relay} is not impacted by the fault type.
- A numerical quadrilateral distance relay with an adaptive relay setting based on constant reactance and constant resistance control strategy for SSSC-ES will avoid distance relay mal-operation.

V. CONCLUSION

In this paper, the impact of emulated reactance and resistance by four-quadrant operation of SSSC incorporating an energy storage device on the transmission line protection is analyzed. An investigation is carried out with symmetrical and unsymmetrical faults on the line. It is clearly shown that SSSC-ES does not affect distance relay performance when it is outside the fault loop. When SSSC-ES is in the fault loop, R_{SSSC}, X_{SSSC} values and hence Z_{relay} will change significantly,

depending on the operating mode of SSSC-ES and control strategy used for SSSC-ES. All these make the distance relay setting a challenging task, and the conventional distance relay with standard settings is shown to mal-operate, i.e. under reach or over reach. A novel adaptive setting for numerical quadrilateral distance relay based on constant reactance and constant resistance control strategy for SSSC-ES is presented to prevent the mal-operation of the distance relay.

Highlights and main contributions of this work are

- A DQ model for SSSC with an energy storage device and in-depth analysis of the impact of operating mode and control strategy for SSSC-ES on the performance of distance relay in all the four quadrants of operation.
- A novel adaptive relay setting based on emulated R_{SSSC} and X_{SSSC} control to prevent the mal-operation of the quadrilateral numerical distance relay for lines compensated with SSSC-ES.
- A reliable protection of SSSC-ES compensated lines presented in this work will help the transmission systems to employ VSC based series compensation integrating energy storage/source, thus utilizing all the four quadrants of operation.

APPENDIX

System Data (All values in pu; Base MVA = 892.4, Base Voltage = 500KV).

Adapted from IEEE first benchmark model

Generator data

Ra = 0; X_d = 1.79; X_q = 1.71; X_d' = 0.169; X_d'' = 0.135; Xq' = 0.228; X_q'' = 0.2; T_d' = 0.4; T_d'' = 0.0259; T_q' = 0.1073; T_q'' = 0.0463; f = 60; H = 5; D = 0;

Transmission system data

R_t = 0.0; X_t = 0.14; Z_{L1} = 0.04 + j1; Z_0 = 0.08 + j2; Xc = 0.45; X_{SYS} = 0.06; V_g = $V_g \angle \theta$; E_b = 1$\angle$0;

SSSC data: 150 MVA; Transformer tap = 1/6; V_{dc} = 0.7pu

REFERENCES

[1] K. R. Padiyar, *FACTS Controllers in Power Transmission and Distribution*. New Delhi, India: New Age International, 2016.

[2] N. G. Hingorani and L. Gyugyi, *Understanding FACTS*. Hoboken, NJ, USA: Wiley, 2011.

[3] M. Venkateswara Rao, S. Sivanagaraju, and C. V. Suresh, "Available transfer capability evaluation and enhancement using various FACTS controllers: Special focus on system security," *Ain Shams Eng. J.*, vol. 7, no. 1, pp. 191–207, Mar. 2016.

[4] A. Bilel, A. Boukadoum, S. Leulmi, and T. Boukra, "Improving the transient stability of the mixed AC/DC networks with FACTS," *Indonesian J. Electr. Eng. Informat. (IJEEI)*, vol. 6, no. 4, p. 477, Dec. 2018.

[5] K. R. Padiyar and N. Prabhu, "Analysis of subsynchronous resonance with three level twelve-pulse VSC based SSSC," in *Proc. Conf. Convergent Technol. Asia–Pacific Region*, 2003, pp. 76–80.

[6] M. Beza and M. Bongiorno, "An adaptive power oscillation damping controller by STATCOM with energy storage," *IEEE Trans. Power Syst.*, vol. 30, no. 1, pp. 484–493, Jan. 2015.

[7] P. R. Ravindra, *Digital Power System Protection*. New Delhi, India: PHI, 2007.

[8] K. Babu, M. Tripathy, and A. Singh, "Recent techniques used in transmission line protection: A review," *Int. J. Eng., Sci. Technol.*, vol. 3, no. 3, pp. 1–8, Jul. 2011.

[9] P. K. Dash, A. K. Pradhan, G. Panda, and A. C. Liew, "Digital protection of power transmission lines in the presence of series connected FACTS devices," in *Proc. IEEE Power Eng. Soc. Winter Meeting. Conf. Process.*, Dec. 2000, pp. 1967–1972.

[10] H. Abdollahzadeh, B. Mozafari, and M. Jazaeri, "Realistic insights into impedance seen by distance relays of a SSSC-compensated transmission line incorporating shunt capacitance of line," *Int. J. Electr. Power Energy Syst.*, vol. 65, pp. 394–407, Feb. 2015.

[11] A. Purohit and V. Gohokar, "Maloperation of distance relay under faulty conditions in presence of static synchronous series compensator," in *Proc. IEEE 2nd Int. Conf. Power Energy Appl. (ICPEA)*, Apr. 2019, pp. 66–70.

[12] T. S. Sidhu, R. K. Varma, P. K. Gangadharan, F. A. Albasri, and G. R. Ortiz, "Performance of distance relays on shunt-FACTS compensated transmission lines," *IEEE Trans. Power Del.*, vol. 20, no. 3, pp. 1837–1845, Jul. 2005.

[13] F. A. Albasri, T. S. Sidhu, and R. K. Varma, "Performance comparison of distance protection schemes for shunt-FACTS compensated transmission lines," *IEEE Trans. Power Del.*, vol. 22, no. 4, pp. 2116–2125, Oct. 2007.

[14] A. H. M. Niaki and I. Dabaghian Amiri, "The impact of shunt-FACTS devices on distance relay performance," in *Proc. 2nd Int. Conf. Knowl.-Based Eng. Innov. (KBEI)*, Nov. 2015, pp. 348–354.

[15] S. Mishra, S. Gupta, and A. Yadav, "Study on factors affecting distance protection scheme of UPFC compensated transmission lines," in *Proc. 1st Int. Conf. Power, Control Comput. Technol. (ICPCT)*, Jan. 2020, pp. 143–148.

[16] A. F. B. Abidin, M. Al-Dabbagh, and A. Mohamed, "Adaptive distance protection relays: An Overview," in *Proc. Eng. Postgraduate Conf. (EPC)* 2008, pp. 1–8.

[17] P. K. Dash, A. K. Pradhan, G. Panda, and A. C. Liew, "Adaptive relay setting for FACTS," *IEEE Trans. Power Del.*, vol. 15, no. 1, pp. 38–43, Jan. 2000.

[18] K. R. Dhenuvakonda, A. Singh, M. P. Thakre, R. R. Karasani, and R. Naidoo, "Adaptive digital distance relay for SSSC based double circuit transmission line using phasor measurement unit," *Int. Trans. Elect. Energy Syst.*, vol. 29, no. 4, p. e2787, Apr. 2019.

[19] M. C. R. Paz, R. C. Leborgne, and A. S. Bretas, "Adaptive ground distance protection for UPFC compensated transmission lines: A formulation considering the fault resistance effect," *Int. J. Elect. Power Energy Syst.*, vol. 73, pp. 124–131, Dec. 2015.

[20] I. Zhang, M. L. Crow, Z. Yang, and S. Chen, "The steady state characteristics of an SSSC integrated with energy storage," in *Proc. IEEE Power Eng. Soc. Winter Meeting. Conf. Process.*, Jan. 2001, pp. 1311–1316.

[21] M. Stella, M. A. G. Ezra, A. Peer Fathima, and C. Khang Jiunn, "Research on the efficacy of unified statcom-fuel cells in improving the transient stability of power systems," *Int. J. Hydrogen Energy*, vol. 41, no. 3, pp. 1944–1957, Jan. 2016.

[22] A. Kazemi, S. Jamali, and H. Shateri, "Effects of SMES equipped SSSC on distance relay tripping characteristic," in *Proc. Transmiss. Distrib. Conf. Expo.*, Apr. 2008, pp. 1–6.

[23] S. Jamali, A. Kazemi, and H. Shateri, "Effects of SMES equipped UPFC on distance relay tripping characteristic," in *Proc. IEEE Power India Conf.*, Oct. 2008.

[24] H. V. G. Rao, N. Prabhu, and R. C. Mala, "Emulated reactance and resistance by a SSSC incorporating energy storage device," *Int. J. Elect. Comput. Eng.*, vol. 9, no. 2, p. 840, Apr. 2019.

[25] IEEE SSR Working Group, "First benchmark model for computer simulation of sub synchronous resonance," *IEEE Trans. Power App. Syst.*, vol. 96, no. 5, pp. 1565–1572, Sep. 1977.

[26] H. V. Gururaja Rao, N. Prabhu, and R. C. Mala, "Investigations on stability of a hybrid series compensated system with SSSC–ES," in *Proc. Int. Conf. Technol. Adv. Power Energy*, Jun. 2015, pp. 57–64.

[27] R. Kirpane and P. P. Bedekar, "Removal of DC offset using digital mimic filtering technique," in *Proc. Int. Conf. Global Trends Signal Process., Inf. Comput. Commun. (ICGTSPICC)*, Dec. 2016, pp. 470–475.

[28] *Model Setting Calculations for Typical IEDs Line Protection Guidelines*, Protection Subcommittee, New Delhi, India, 2014.

[29] A. B. Oza, N. K. C. Nair, R. P. Mehta, and H. V. Makwana, *Power System Operation and Switchgear*. New York, NY, USA: McGraw-Hill, 2010.

H. V. GURURAJA RAO received the B.E. degree in electrical engineering from Karnatak University, in 1989, the M.Tech. degree in power systems from the University of Mysore, in 1993, and the Ph.D. degree from Visvesvaraya Technological University, in 2020. He was a Faculty Member of electrical and electronics engineering with the KVG College of Engineering, Sullia, from 1993 to 2004. He is currently an Assistant Professor (selection grade) in electrical and electronics engineering with the Manipal Institute of Technology, Manipal. His research interests include power system protection, stability, power electronics application to power systems, and embedded systems. He is a Fellow of the Institution of Engineers, India, a Life Member of the Indian Society for Technical Education, and a member of the Institution of Engineering and Technology.

R. C. MALA received the B.E. degree in electrical power engineering and the M.Tech. degree in power systems from the University of Mysore, in 1988 and 1992, respectively, and the Ph.D. degree from Visvesvaraya Technological University, in 2020. She was a Faculty Member of electrical and electronics engineering with the KVG College of Engineering, Sullia, from 1992 to 2004. She is currently an Associate Professor in electrical and electronics engineering with the Manipal Institute of Technology, Manipal. Her research interests include power system dynamics, power electronics application to power systems, and control systems. She is a Fellow of the Institution of Engineers, India, and a Life Member of the Indian Society for Technical Education.

● ● ●

NAGESH PRABHU (Senior Member, IEEE) graduated in electrical engineering from the Institution of Engineers, India, in 1991. He received the M.Tech. degree in power and energy systems from N.I.T. (Karnataka Regional Engineering College), India, in 1995, and the Ph.D. degree from the Indian Institute of Science, Bengaluru, India, in 2005. He is currently a Professor and the Head of the Electrical and Electronics Engineering Department, N.M.A.M. Institute of Technology (Nitte), India. His research interests include power system dynamics and control, HVDC, FACTS, and custom power controllers. He is a Life Member of the Indian Society for Technical Education and a Fellow of ISLE, India.